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In situ soil respiration at reclaimed and unreclaimed post-mining sites: Responses to temperature and reclamation treatment

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ABSTRACT

Soil respiration accounts for much of the CO_2 released from terrestrial ecosystems into the atmosphere. Although respiration depends on temperature, the relationship between respiration and temperature may vary among soils. Here, we measured soil respiration and soil temperature in chronosequences of reclaimed and unreclaimed post-mining sites (10–50-year-old coal mining heaps near Sokolov, the Czech Republic) to determine the major factors affecting temperature-dependent soil respiration. Soil respiration was repeatedly measured in situ during 2011 and 2012 at five reclaimed sites (planted with alder) and five unreclaimed sites (overgrown with willow, birch, and aspen). In addition, spatial heterogeneity was assessed by repeatedly measuring soil respiration at 30 permanent points at one 28-year-old site (the "30-point" site) in 2007–2008. In all sites root biomass, soil carbon (C) content, soil pH, and the thickness of Oe layer were also measured.

In the chronosequences and 30-point site, the relationship between soil respiration and temperature increased with soil C content; soil respiration was unrelated to temperature if soil C content was <9%. The increase in respiration with temperature was enhanced by a thick Oe layer and by high root biomass.

Soil respiration at reclaimed sites increased with site age to age 30 years and then decreased. The decrease in respiration at the older sites was associated with a decrease in soil temperature (associated with increased shading). Respiration at unreclaimed sites increased with age and was usually lower than in reclaimed alder plantation of similar ages.

1. Introduction

Open-cast coal mining causes massive disturbance to ecosystems. In this kind of mining, a large amount of overburden spoil material overlaying coal layers is excavated and deposited in vast spoil heaps, and the affected ecosystems are either erased by excavation or buried by heap dumping. The spoil material typically has very low biological activity (Frouz et al., 2001; Helingerová et al., 2010). The recovery of spoil heaps depends on the formation of soil (pedogenesis), and especially on reconstruction of soil biological functions (Bradshaw, 1997).

Soil contains two- to three-times more carbon than the atmosphere, and CO_2 efflux from soil, or soil respiration, supplies most of the CO_2 that moves from terrestrial ecosystems to the atmosphere (Subke and Bahn, 2010). Soil respiration can be a sensitive indicator of overall metabolic activity of soil and can be used as a measure of soil recovery in restored ecosystems (Helingerová et al., 2010). Soil respiration has two major components, which are heterotrophic respiration (based on decomposition and mineralization of soil organic matter, largely by microorganisms) and root respiration.

At global, regional, and local scales, soil respiration is greatly affected by soil temperature (Subke and Bahn, 2010). Factors affecting soil respiration and its relationships with temperature, however, are complex and include soil moisture, carbon availability, and the relative contribution of root respiration (Fontaine et al., 2004; Davidson et al., 2006; Bahn et al., 2010; Subke and Bahn, 2010). As a consequence, relationships between soil respiration and temperature vary substantially among soils depending on soil

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Table 1
Soil properties (mean ± SD) at sites in an unclaimed and reclaimed chronosequence and at a 30-point unclaimed site in open-cast mining heaps in the Czech Republic. The number associated with each site name is the site age in years. Reclaimed sites are labeled with an R, and unreclaimed sites are marked with either T (indicating the top of a wave) or B (indicating the bottom, i.e., the depression between waves).

Site	C content (%)	Root biomass ($g\,m^{-2}$)	pH	Oe thickness cm	Soil temperature (°C)
Unreclaimed					
8B	6.3 ± 0.6	34 ± 30	7.1 ± 0.1	0 ± 0	21.6 ± 4.8
8T	3.9 ± 0.9	23 ± 21	7.7 ± 0.1	0 ± 0	22.4 ± 5.7
18B	6.2 ± 0.9	38 ± 20	7.9 ± 0.1	0 ± 0	21.8 ± 3.7
18T	4.3 ± 0.1	31 ± 19	7.8 ± 0.0	0 ± 0	25.5 ± 4.4
20B	6.3 ± 0.1	228 ± 50	7.7 ± 0.1	1 ± 0	18.8 ± 3.7
20T	5.1 ± 0.1	43 ± 28	7.7 ± 0.1	0 ± 0	21.6 ± 5.5
28B	27.4 ± 4.7	342 ± 68	7.4 ± 0.1	6 ± 1	15.2 ± 1.5
28T	10.5 ± 2.7	29 ± 38	7.3 ± 0.1	0 ± 0	15.6 ± 1.9
52B	11.6 ± 0.5	503 ± 450	7.6 ± 0.1	1 ± 0	18.1 ± 2.7
52T	5.8 ± 1.4	40 ± 36	7.3 ± 0.1	0 ± 0	19.6 ± 3.9
Reclaimed sites					
R10	6.9 ± 0.3	147 ± 102	8.0 ± 0.1	0 ± 0	19.6 ± 3.8
R18	11.0 ± 0.1	81 ± 37	8.0 ± 0.1	0 ± 0	16.6 ± 2.3
R33	8.9 ± 0.3	110 ± 33	7.5 ± 0.2	0 ± 0	16.4 ± 2.1
R35	12.7 ± 0.4	75 ± 29	7.1 ± 0.1	0 ± 0	15.5 ± 2.7
R55	9.6 ± 0.6	161 ± 80	7.4 ± 0.1	0 ± 0	14.5 ± 2.1

origin, previous management, tree species soil fauna activity etc. (Chodak et al., 2009; Chodak and Niklińska, 2010; Frouz et al., 2013). In many cases, soil respiration is closely related to soil temperature in organic soil but not in mineral soils. Although laboratory experiments that study heterotrophic respiration and in situ measurement of the decomposition of fresh litter often indicate that soil respiration rates are greatly affected by soil temperature, long-term measurements of decomposition in mineral forest soils indicated that soil respiration was independent of temperature (Giardina and Ryan, 2000). The authors of the latter study concluded that decomposition in mineral forest soils is limited by the availability of substrate to heterotrophic microorganisms rather than by temperature. Other studies have also indicated that the response of soil respiration to temperature depends on the availability of soil organic matter (Reichstein et al., 2000; Uwe and Kirschbaum, 2006; Liu, 2013).

The principal hypothesis of this study was that the strength of the relationship between soil respiration and temperature will increase as soil C content increases. The objectives of this study were to: (1) describe the temporal and spatial variation in soil respiration at reclaimed and unreclaimed alder plantations in post-mining sites that provide different soil organic matter development; (2) describe the relationship between soil respiration and temperature; and (3) determine the major factors affecting the relationship between soil respiration and soil temperature at these sites.

2. Methods

2.1. Study sites

The study was done at heaps produced by open-cast coal mining near Sokolov in the Czech Republic (50°14′21″ N, 12°39′24″ E), altitude 500–600 m a.s.l. At the study sites, the mean annual precipitation is 650 mm, and median annual temperature is 6.8 °C. The spoil heaps consist of tertiary clay shales (Frouz et al., 2001; Šourková et al., 2005). The pH of the substrate is alkaline in initial successional stages and gradually decreases with site age (Table 1). The spoil material also contains significant amounts of fossil organic matter (Frouz et al., 2011a).

We used two chronosequences. The first one consisted of five sites reclaimed by the planting of alder, (*Alnus glutinosa* and *Alnus incana*) 10, 18, 33, 35, or 55 years before the present study (Table 1). This is the most common reclamation measure in the area, vegetation development is quite fast canopy closures in about 10 year old sites. The second chronosequence consisted of five unreclaimed sites on heaps that were deposited 8, 18, 20, 28, and 52 years before the present study and that were spontaneously colonized by vegetation (especially by *Salix caprea*, *Betula pendula*, and *Populus tremula*), the vegetation development is slower than in reclaimed sites, canopy closures in about 20 year old sites (Frouz et al., 2008) (Table 1).

The reclaimed sites had been leveled by earthmoving machinery before trees were planted. In contrast, no such procedure was carried out at the unreclaimed sites, which are characterized by longitudinal rows of depressions and elevations, or "waves", formed during the heaping process. The top of a wave was about 1–2 m above the bottom of the depression, and individual waves were about 6 m apart. Site age was calculated since the last major disturbance, which was heaping for unreclaimed sites and leveling for reclaimed sites.

2.2. Measurement of soil respiration, soil sampling, and sample processing

Two data sets were used in this study. The first data set was based on 30 measurement points at one site, which was a 28-year-old unreclaimed site covered by spontaneous regrowth (birch aspen willow) and which is hereafter referred to as the "30-point site". The second data set contained data from all sites of both chronosequences (reclaimed and unreclaimed) described above. Because of the wave-like surface and large spatial heterogeneity, two microhabitats were studied at the unreclaimed sites: the tops and bottoms of the waves (hereafter referred to as top and bottom microhabitats). In each reclaimed site and in each microhabitat of each unreclaimed site, four measurement points were established and were marked with stakes.

Measurements were made at the 30-point unreclaimed site in 2007 and at the chronosequence sites in 2010. In both cases, respiration was in situ measured each month from April to September with an SR1000 CO_2 analyzer (ADC UK©). This instrument works as an open system that uses an infrared CO_2 analyzer to measure the CO_2 concentration in air entering and leaving a respiration chamber, together with air flow through the chamber. Soil temperature was recorded during respiration measurement at 2 cm depth by a temperature sensor that was integrated with the SR1000 gas analyzer. For each sampling point, three reading 20 s apart were taken and averaged. In both cases we start measurement at different